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Off-Highway Tire/Road Damage and Healing Mechanisms

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Off-Highway Tire/Road Damage and Healing Mechanisms

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CONTENTS

Page No.

INTRODUCTION 1
UNPAVED ROAD SURFACES 1
Unpaved Road-Surface Healing Methods 1
Unpaved Road-Surface Failure Criteria 1
Tire Slips and Soil Movements 4
Evidence for the Slip Concepts. 4
Models for Slip Sinkage 5
Needed Changes in Vehicular Operations 5
Soil Compactability 6
In the Laboratory 6
In Road Operations 6
Washboarding Cycle. 6
Tire Effects 7
SUMMARY 8
CONCLUSIONS 8
RECOMMENDATIONS 9
REFERENCES. 9

ILLUSTRATIONS

Figure No. Page No.

1. . . . . Coulomb-Mohr diagrams for sand, clay, and mixed soil. 2
2. . . . . .Ultimate bearing value from conditions of plastic equilibrium 2
3. . . . Shearing damage after 50 passes with 37.5-39 tires at 80 kips and 100 psi on 3-inch gravel surface-treated with Dustgard 3
4. . . . . Increased damage caused by braking while straddling original ruts. 3
5. . . . . . Horizontal force and slip sinkage vs. horizontal movement for a shear plate 5
6. . . . . .Bias-ply tire and its footprint. 7
7. . . . . The cornplanter tires effect 7
8. . . . . Radial tire and its footprint 7

INTRODUCTION

To further easy understanding, only two types of road surfaces need to be recognized. First, there is soil, which may be sod, earth, straw, gravel, crushed stone, coal, minerals—or any convenient material that packs well enough to support traffic. When a tire is moved in soil, the soil gives way.

Second, at least from a conceptual viewpoint, any loose soil can be mixed with a cementing agent—such as Portland cement, bitumens, resins, tars, etc.—and bound into a compact, monolithic pavement surface that no longer gives way under tire forces. Thus, in all that follows, only two types of road surfaces are considered—unbound and bound. These can also be referred to as unpaved and paved or off road and highway.

UNPAVED ROAD SURFACES

Unpaved road surfaces deteriorate by flooding and also by rutting, dusting, and washboarding when road strengths cannot withstand traffic stresses. Machine maintenance is then needed to correct the conditions that cause continued deterioration. Correction is preferred to mere restorative maintenance; the road should improve with use, not continue to deteriorate.

Further, in nations where paved highway systems predominate, soil roads suffer special abuse from highway vehicles. Vehicular off-road damage becomes commonplace, and continuous restorative maintenance becomes a way of life. The types of vehicles and tires, and the manner and times they are used, can determine whether an unbound road will improve or quickly deteriorate again. Off-road design features and maintenance practices can favor or prevent the necessary changes in vehicle use.

Unpaved Road-Surface Healing Methods

The mechanisms by which ruts are made, soils are loosened, and washboards are formed are reversible and can be related by classic soil-failure theorems to mechanical properties of the soil (or aggregate) that is being changed. Soils cannot be compacted if too wet, since the space between particles is already filled with water; or when too dry, since wet interparticle attractions are absent and friction impedes compactive particle movements. When properly moistened (or with adequate moisture retention), well-compounded soils can be compressed by pneumatic-tired rollers into compact, strong, pavement-like surfaces.

Soils have practically no tension forces; they tighten from pressure and loosen from shear. If a compactible soil is too loose, shearing due to lateral soil-support stresses and longitudinal-travel stresses can undo the compressive effects of rolling, and the soil is further loosened. If the soil is moderately compacted, tire-contact pressures must be increased to greater than the road's surface strength for further compaction to take place.

When soil, water, and pressure are favorable, washboards and ruts can be removed and the surface smoothed by compactive rolling without reducing the thin road-surface layer by surgically blading away its high spots. These restorative operations can occur ideally with almost complete reversability; soils can often be induced to rotate and return to their original positions along practically the same failure trajectories from which they were displaced.

Unpaved Road-Surface Failure Criteria

To understand the reversible role of modern tires that are on new-design vehicles, and to operate them wisely, it is necessary to understand how wet and dry soils become rutted, compacted, loosened, and washboarded by the tires that travel upon them. Soils fail by shearing, and the static shear strengths of frictional (sand), cohesive (clay), and mixed soils are commonly interpreted by Coulomb-Mohr diagrams (fig. 1). Soils are presumed to fail by shearing when shear stresses exceed

$$s = c + p \tan \phi \qquad (1)$$

Practical soil-failure criteria are determined by adjusting the apparent soil pressure for the effects of water and air-pore pressures and their unloading times, in much the same sense that tire engineers consider tread grooves for relieving hydroplaning pressures.

The bearing capacity of a long soil foundation is similar to the bearing capacity of a loaded, long tire/soil contact patch. A pressure bulb of soil is confined under the foundation by the shearing resistance of surrounding soil on its sides. The pressure bulb is at first delineated elastically by ovals of constant pressure under the foundation. These define two orthogonal systems of maximum shear stress; each system intersecting the constant-pressure ovals at 45-degree angles.

Prandtl (working with metals) considered the limiting elastic equilibrium case, just before flow starts, and found the bearing pressure strength (1) to be

$$q = \frac{c}{\tan \phi} \left[\tan^2 \left(45^\circ + \frac{\phi}{2}\right) e^{\pi \tan \phi} - 1 \right] \qquad (2)$$

At this point the pressure bulb is replaced by stable,

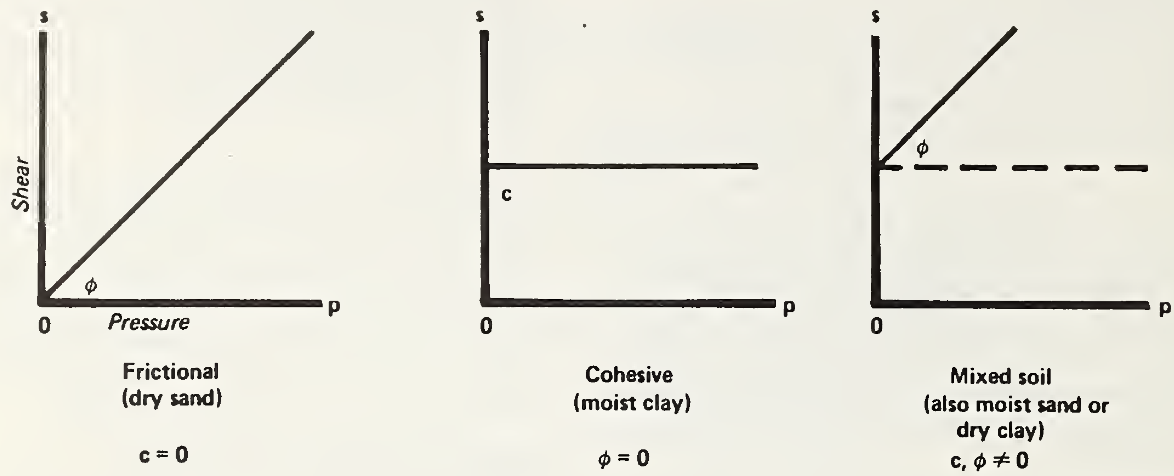

Figure 1. Coulomb-Mohr diagrams for sand, clay, and mixed soil.

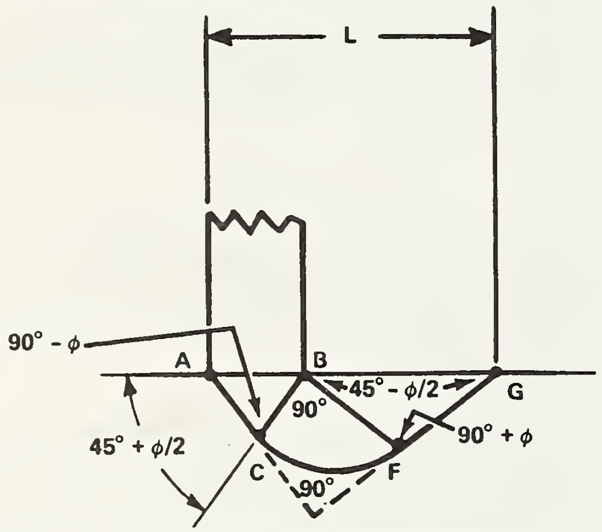

Figure 2. Ultimate bearing value from conditions of plastic equilibrium.

compressed soil in triangle ABC (fig. 2), and the surrounding soil is outlined by boundary BC, surface line BG, and a line of incipient soil failure CFG—with a logarithmic, spiral segment CF and a straight-line segment intersecting the soil surface at the constant angle $45^{\circ}-\phi/2$. Radial lines of shear failure from B (not shown) define the spiral-failure boundary by intersecting it at the constant angle $90^{\circ}-\phi$.

Terzaghi adapted Prandtl's solution for use with noncohesive (sandy) soils, in which c = 0, by replacing the c of equation (2) by $c + c'$, where

$$c' = \frac{w}{L} \tan \phi \qquad (3)$$

and w is the weight of a unit-thickness slice of soil contained in the boundary ABGFC. These, and many other formulae for various soils, soil layers, foundation depths, shapes, and loads, are respectfully acknowledged by the authors; but it would be out of place to go further. The Prandtl-Terzaghi model well illustrates our introductory points.

The effects of longitudinal braking and propulsion stresses (without gross tire slip) are to load the failure boundary CFG with longitudinal ("into the paper") shear stresses. These combine at right angles with the outward shear stresses already on the failure boundary. The passive triangle BFG slips outward, releasing the spiral sector BFC that supports compressed soil ABC. Thus, the tire sinks deeper.

The mechanism is self-escalating. Deeper ruts create increased tractive resistance to the travel of the tire. These increased travel forces combine with earlier shear stresses on the boundaries of the soil-failure prism, causing it to move further outward and allowing the tire to sink deeper. Soil compaction takes place beneath the tire and the failure zones, and soil shears take place on the sides, in front, and (to a lesser extent) behind the tire. The net effects are to compact deeper soils and loosen surface soils outside the wheel rut.

These Prandtl-Terzaghi rut failures are normally obscured by random travel of successive vehicles, but can be seen clearly

Figure 3. Shearing damage after 50 passes with 37.5-39 tires at 80 kips and 100 psi on 3-inch gravel surface-treated with Dustgard.

when precise steady-state vehicle tests develop the rut under constant conditions. Figure 3 (courtesy Boeing Aerospace Co.) shows clearly that the failure crackline (corresponding to point G in fig. 2) breaks the ground surface far outside the wheel rut.

Figure 4 shows the increased sinkage that occurs when longitudinal braking forces are applied to a rolling tire on sandy soil. The crackline became visible because of a thin, brittle overlay of compacted-gravel aggregate on the sandy soil in figure 3, and is obscured by loose sand, but exists similarily in figure 4.

Figure 4. Increased damage caused by braking while straddling original ruts.

Similar soil movements take place in the direction of travel, but the loading is no longer symmetrical and shear becomes continuous as the unsymmetrical Prandtl-Terzaghi diagram (analogous to fig. 2) travels forward with the wheel. Automotive mechanisms go beyond classic static-failure criteria at this point. Instead of designing to avoid failure stresses, off-road vehicle problems are concerned with continuous soil failure, how far it occurs, and the soil changes that accompany it. These changes are related in the laboratory to the soil sinkage and shears induced by wheel and track loads and slips.

Tire Slips and Soil Movements

The measured slips of tires on pavement, and in soils, are different because tires are elastic and soils are not. Tire slips are measured in percentages and soil slips in inches. This difference is critical, because tire and soil investigators apparently do not understand each other's measurements.

The tire-on-pavement slip problem was explained in an analogous form many years ago as the belt-on-pulley slip problem (2). A belt enters its arc-of-pulley contact at one tension and leaves it at another. The change in tension causes an elastic change in belt strain, which is released as slip at the end of the arc of contact. Hence, belt strain and relative slip (actual slip distance divided by travel distance) are equal.

Therefore (by Hooke's law), for small slips, belt stress is proportional to relative slip. At higher slips, the linearity falls off when slip occurs within the arc of contact rather than at the end of the arc. Similarly, a tire performs as a compression belt driving upon the pavement. The tractive quotient

$$\begin{aligned} \mu &= \text{tire tractive stress/tire normal stress} \\ &= \text{tractive force/normal force} \end{aligned} \tag{4}$$

is related consistently to relative slip curves over wide variations in tire load. The load changes cause contact-area changes such that patch stresses remain practically constant for equal μ levels. For these reasons, slips are commonly presented as percentages of travel distance when tires-on-pavement μ-slip curves are reported.

For two reasons, these unqualified μ-slip curves become meaningless (3) when tires are tested on soil:

1. The gravel-soil aggregate is bound into monolithic, rigid pavement surfaces by cementing agents. When the tire moves back to the same unbound aggregate on an ordinary soil road, Hooke's law and relative slip concepts again demand that the tire rubber/gravel interface slip be the same as it was on pavement. The additional measured wheel slip takes place in the soil.

2. Soils are inelastic. The soils' lateral resistance is a function of the lateral distance that the soil is moved. Examples:

- A tire with a 1-ft contact-length patch slips 1 percent on pavement and 3 percent on similar compacted gravel at the same μ level. This leaves 2 percent tire slip expended in the soil, and the total soil movement is 0.02 x 1-ft contact length = 0.02 ft.

- A crawler track of 10-ft length with 2 percent apparent soil slip moves the soil 10 x 0.02 = 0.2-ft in shear. A tire with a 1-ft contact-length patch and 20 percent apparent soil slip also moves the soil 1 x 0.20 = 0.2-ft in shear.

The misunderstanding appears to be widespread in sales brochures and soil-damage studies wherein tires, by comparing only their relative slip quotients, are depicted to be ten times more damaging than tracks.

Evidence for the Slip Concepts

External evidence for the foregoing slip concepts occurs in a variety of ways:

1. Slip corrugations appear when steady-state traction tests are taken on nonabrasive pavements. The corrugations appear perpendicular to the direction of slip. Dividing the pitch distance between corrugations by the contact length in the direction of travel often yields the percent slip quite accurately.

2. When soil roads are loose, tractive efforts—measured at different inflations and contact lengths—correspond to actual slips and, hence, to lineal movements of soil. When the same tests are repeated on the same road after compaction to a pavement-like surface, measured tractive efforts then correspond to percent slips; the contact length no longer is effective after soil slip is eliminated.

3. Tire-wear tests at equal tractive efforts on both paved and corresponding crushed-gravel aggregate soil roads appears to be comparable when the interfacial slip on the soil road is assumed to be equal to the slip measured on the pavement (3). Slip energy vs. wear comparisons are used in this

manner to estimate tire wear on loose gravel roads from similar wear tests performed on pavements. The additional measured slip apparently is expended in the soil.

Models for Slip Sinkage

Realistic prediction of the impact on a soil road of any proposed heavy-hauling program demands that credible models be conceived to limit such factors as loads, contact pressures, slips, and number of vehicle passes to pre-set damage levels. Tire-contact patches and laboratory test plates usually differ, so that both tests are needed for correlation. If adequately scaled and interpreted, however, laboratory tests can become fair guides as to what can happen to the road and what can be done to prevent greater damage than desired. In their present state, the laboratory tests need to be extended to include the effects of ordinary preventive measures.

Figure 5 shows a well-known set of curves from Reece's tests of flat plates on wet sand. The curves are taken at constant pressures and depict sinkages and tractive-force levels for increasing lineal slips of the plates on the sand. Successive wheel slips would conceivably follow the same curves and yield increased sinkages and tractive forces. However, free-rolling wheels would presumably cause no slip and hence, contrary to experience, no sinkage—so something is missing.

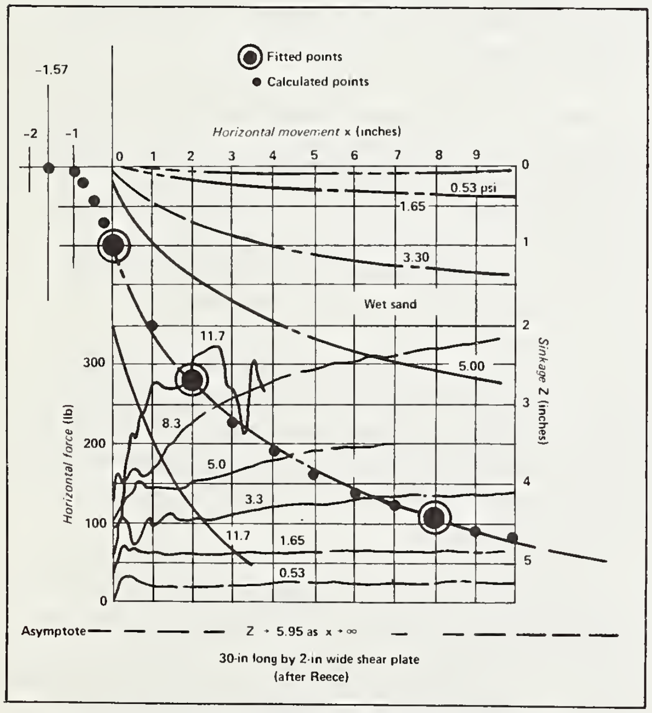

Figure 5. Horizontal force and slip sinkage vs. horizontal movement for a shear plate.

The difficulty lies in the two-step nature of the laboratory test. First the plate is loaded, without slip, to the test pressure and initial sinkage. Then, secondary sinkage is measured as the plate is slipped horizontally to develop the test curve. In contrast, wheels slip continuously across the test soil with no break in the test curve. Evidently, some latent slip must be introduced to develop the patch for the wheel's approaching, rather than being vertically pushed into the soil. The slipping wheel could then conceivably follow the same sinkage path.

To model the fictitious wheel and its initial slip, the equation

$$Z = (AB^{x})^{\frac{1}{1 + cx}} \tag{5}$$

has been fitted to three points on Reece's 8.3-psi curve to obtain sinkage

$$Z = (1.03 \times 3.111^{x})^{\frac{1}{1 + 0.6366x}} \tag{6}$$

as an explicit function of slip x. The fit appears to be satisfactory, so equation (6) was used to calculate the ultimate sinkage

$$Z_{\infty} = B^{\frac{1}{c}} = 5.95 \text{ inches} \tag{7}$$

as slip x approaches infinity, and the initial slip x approaches $-1/c = -1.57$ inches as Z approaches zero.

If the extrapolations are plausible, the resulting model has several interesting features:

1. Rolling wheels could be modeled by adding 1.57 inches of slip for each rolling tire.

2, Tractive wheels could be modeled by adding 1.57 inches, plus the measured slip, for each tractive tire.

3. The total sinkage from a number of vehicles could be calculated from equation (6), with slip x equal to the sum of all the slips.

4. If soil pressure remains at 8.3 psi, the total sinkage for an infinite number of vehicles cannot exceed the asymptotic value of Z = 5.95 inches.

Needed Changes in Vehicular Operations

Truck drivers follow each other's ruts when safety and mobility are marginal, but can become fully cooperative and travel uniformly over an entire off-road surface when its

width and edge strength make such travel safe. Redirection of drivers and road designers must go together if ruts are to be replaced by uniformly compacted, strong road surfaces. From both the Prandtl-Terzaghi and the modified slip-sinkage curves models, it becomes clear that soil-contact pressures and slips must be drastically reduced, when roads are weak, to make such driver redirection possible. Drivers will not leave their ruts if it means getting stuck. From a drainage sandpoint, ruts are intolerable in wet weather. The trapped water soaks into level roads and erodes mountain roads.

Soil Compactability

In the Laboratory. The washboarding and decompaction of dry roads and the rutting of wet ones both depend on the technical definitions of "wet" and "dry." In soil tests, optimal moisture is defined by compaction tests, as the water content at which maximal soil dry density is achieved. Test curves at constant compactive energy, generated by dropping weights onto confined soil, show density to become less when compaction is attempted at water contents that are "wet" when above optimal and "dry" when below.

Compaction tests are performed by careful, standard procedures—but valuable tire/road insights can be obtained by experimenting with the sample after the test is over:

1. If a small amount of water is added to the optimal compacted sample, and the weight is then repeatedly dropped upon it, nothing happens until enough water has been added to approach the sample's saturation point at that density. Beyond this moisture content, pore pressures during impact decompact the sample until the pressures are relieved—but no further.

2. If, instead, the optimal compacted sample is further dried, no swelling takes place. Repeated weight drops do not decompact the dried sample. The soil is confined in the test cylinder; no shear (and, hence, no decompaction) takes place.

In Road Operations. Decompacted wet roads can be restored by rolling them under optimal moisture as the road dries out. Compaction is slower, but continues—after drying—well past the optimal moisture content for the test because the moist, compact road surface doesn't shear under the roller.

Since soil shear causes decompaction of dry roads, reducing bearing pressures and tractive exertions help hold the road together. Recompaction requires that water be restored by wetting or with hygroscopic agents. Pneumatic rollers compact a soil because tire pressures are, at first, lowered to minimize soil shear, and then gradually are raised to remain effective as the soil becomes stronger (4). Uniform rolling of the entire surface prevents rut formation.

When roads are compact and rut-free, water quickly runs off and the hygroscopic agents remain in the road soil. When the soil is loose or rutted, the road soil becomes permeable and soaked by standing water. The rate of hygroscopic agent leaching loss rises from negligible to high when rain water passes through the water rather than over it.

Washboarding Cycle

Washboarding of dry soils is a vibratory problem in which the elastic road/tire/suspension system is excited by periodic soil slips. The tire slips and, consequently, sinks deeper. This sinkage causes both increased contact and increased vertical loads as the sinkage is arrested. Slip stops, and the tire rebounds elastically by climbing back to a level corresponding to zero slip. The climbout is very rapid, because the tire rotates more rapidly when slipping. As the climbout ends, the tire load becomes lighter from vertical deceleration and the tractive force remains constant. The increased μ level frees the tire, which again slips and the cycle is repeated.

Rolling trailer tires do not slip and, hence, are much less prone to start washboards, although—if resonant—they can magnify them. Wet roads rarely washboard; damping prevents the sudden tire release of tractive slips. If washboarding does occur, it is more likely to be induced by cyclic bearing stresses.

The washboarding cycle can be deactivated by lowering the rebound or by increasing the damping. If the tire-contact length is increased and flattened, the climbout angle that feeds the rebound is reduced and the long contact length is progressively released from rear to front—rather than abruptly. This further dilates the rebound release shock and retains partial tire contact with the road.

This partial contact reduces the sudden increase in tire rotation caused by the elastic tire release that cycles the changes in tire slip; thus, effectively damping this essential part of the mechanism. Healing begins, and the washboards are ironed out by successive passes of long-contact, non-washboarding tires.

Tandem axles can be excited to washboarding behavior by bogey-hop. The mechanisms are similar to single axles for each tire, with additional excitation possible when arrested slip in one axle causes increased slip in the other, less-loaded one. Interaxle damping can become inadequate when torsional drivetrain frequencies combine with similar

bogey oscillation frequencies to form a periodic forcing function for the washboard cycle. Detuning the axle suspension, or damping its drivetrain, are possible alternates.

Tire Effects

Both bias and radial tires resemble rigid wheels when inflated to pressures far above the soil's strength. They then differ only in the crown contours of the tires. Differences of soil concern appear when the tires are deflated towards soil-strength pressure levels.

A bias-ply tire (fig. 6) squirms across an hourglass-shaped footprint because the bias chords AB spread the tire diagonally when it is flattened to the road. The resulting footprint causes diagonal slip of the tread on the road. Thus, a bias-ply tire acts like a pair of cornplanter tires (fig. 7) when it goes down the road (5).

A radial tire (fig. 8) has a flat bottom, so the tread remains flat, and points AB are spread in two swellings, A and B, on the side of the tire—rather than at the road surface. Consequently, it has a rectangular footprint without scrub or squirm slip due to the tire.

For both types of tires, agressive tire treads accelerate the decompaction of dry road surfaces. With passive treads, the radial tire causes less surface shear and decompaction because of reduced diagonal slip in the tire patch. The radial tire is ideal in shallow ruts.

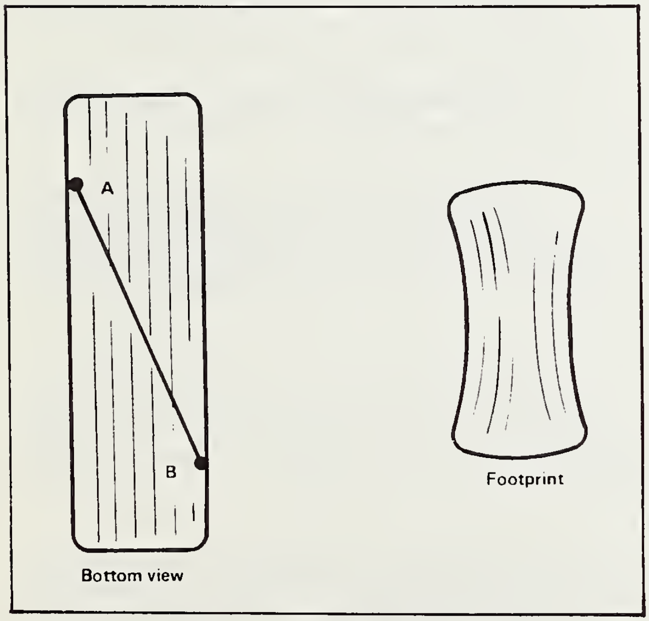

Figure 6. Bias-ply tire and its footprint.

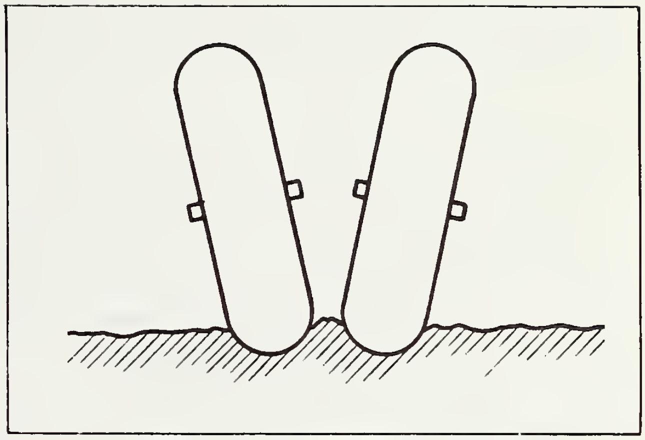

Figure 7. The cornplanter tires effect.

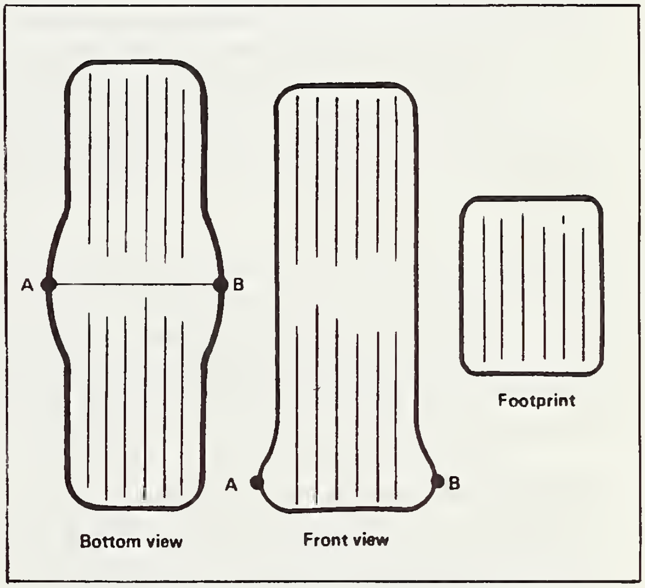

Figure 8. Radial tire and its footprint.

The bias tire, acting like a pair of cornplanter tires, gives (arguably) confining support to the pressure bulb by inward shear components at the front of the tire/soil contact patch. These shears could be beneficial when the soil is compactible, and detrimental when it is not. The bias tire sometimes binds by rubbing the walls of narrow, deep ruts.

Developments for both bias-ply and radial tires have created a new dimension for adjusting ground-contact areas by varying tire inflation. Tire deflections from 40 to 50 percent of the section height and adjustable pressures from 10 to 70 psi have become feasible adjustments for road and speed conditions. Central tire inflation systems that adjust

tire pressures while traveling are no longer limited by narrow tire operational envelopes—or worse, by trained ignorance from lurid tire blowout advertisements that paralyze these beneficial adjustments.

Vehicles can move efficiently, with little power consumption (and, therefore, minimal soil disturbance) on soft terrain, then increase pressures to travel gravel roads at moderate speeds without washboarding, and finally travel highways at full inflation and high speed to their destination. Reduced power consumption goes far beyond the price of fuel. Road destruction is caused by wasted energy. Reducing waste energy and reducing unbound road destruction are thermodynamically inseparable reactions.

SUMMARY

When soils are compactable, they are compacted by compression and loosened by shear. Soil shearing is caused outside the tire-contact patch by combined tractive and lateral shears resulting from tire-contact pressures being too high for the lateral-support strength of the soil (6). Both the tractive and lateral-support shears are reduced by increasing the tire-contact area and, thus, reducing tire sinkage and propulsion resistance. The combined reductions enable pneumatic rollers to smooth and recompact the road surface.

Washboards are caused by cyclic rebounds and climbouts from cyclic soil shears. Increasing the length of contact lowers the soil pressure and shear, decreases the climbout angle, and inhibits the sudden release of the tire from the soil—thus eliminating washboarding by eliminating its source of power input.

These new developments are outdating older "heroic" approaches to off-road mobility problems. Tactical questions of whether it will leave the road in such a condition that other vehicles can follow. In this light, questions of whether enemy efforts, weather, or friendly vehicles cause greater damage to roads can bring embarassing answers. Destruction of a military road system is usually a self-inflicted wound. The roads of Flanders and the Ukraine served local residents well until uncontrolled military operations turned them into impassable quagmires.

Quagmired roads take weeks to dry out; but well-crowned and compacted roads shed most of the water and dry to usable levels within a few hours. Road-closure times are usually trival compared to the road-quagmire periods that follow if damage is permitted. Because of large amounts of available power, soil road systems are open to unlimited waste energy inputs and proportionate damage when soils cannot carry traffic efficiently.

Central tire inflation (CTI) systems can convert road-user vehicles to effective road-rolling tools. Pressures, loads, and operations can be adjusted so that all traffic becomes part of the road maintenance team. Washboards, ruts, and soil loosening can be reversed by road, soil, and vehicle changes that reduce the soil shears that cause the damage. The entire road surface should be accessible for travel use so that redirected drivers can furnish continuous restorative maintenance to the soil road surface.

Mere axle loads, without consideration of contact pressures and shears, are incapable of describing a soil road's ability to sustain traffic. The road's weakness must ultimately be judged by the rate at which it consumes the waste energy that destroys it.

The authors have tried to bridge a few large gaps between workers in roads, vehicles, and tires. Some indulgence is begged of experts in all three disciplines.

CONCLUSIONS

The newer developments in tire and vehicle technology offer significant opportunities for reducing the abuse of soil roads by conventional highway vehicles. The reductions in ground contact pressure also can bring lower stresses to light paved road construction. These benefits cannot be realized by mere purchase of new tires and deflation systems, however. The combined efforts of truck and tire engineers, road design and maintenance engineers, and truck drivers and road managers are needed to harvest the benefits of the newer technological developments.

1. Drivers must be trained to operate the tire pressure controls and to cease driving in each others ruts.

2. Road designers must provide wider and stronger road edges to make the drivers' changes possible.

3. Truck operators must be induced to buy the new CTI equipment by sharing some of its benefits and/or penalizing the damage caused by those who refuse to take part in the "self-maintained road" approach.

4. Road jurisdictional authority must also assume the responsibility that goes with such authority. Roads must be closed to such vehicles at such times that hauling would be destructive to the road.

5. Tire and truck builders must see some serious purpose ahead in order to produce the new equipment for the civilian market. They cannot produce equipment if no one bothers to buy it.

6. The benefits of reduced construction and maintenance costs will be lost if no changes are made in either construction or maintenance.

The road, truck, driver, maintenance operations, and operational policies are all interdependent parts of a close-linked local transportation and investment system. If each operates with disregard of the others, improvements in any one of them will be mostly wasted. By working together, each can not only contribute more to the road system, but can do so with much reduced effort, use of men, machine, energy and materials.

RECOMMENDATIONS

1. Investigate the feasibility of operating logging trucks with improved tires and inflation systems (CTI).

2. Determine savings in road construction and maintenance and vehicle maintenance that can be achieved by good CTI use and management.

3. Train drivers, maintenance, design, and road operational managers to make optimal use of CTI benefits. For this purpose:

a. Operating loads and pressures must be determined for varying road conditions.

b. New design needs must be established and balanced with investment alternates.

c. Practical tests must be developed to enable road managers to control hauling traffic without indecision and bickering.

4. Progress in the above efforts should be followed by setting a good example with Forest Service vehicle operations and by encouraging other traffic to similar improvements in knowledge, skill, and road use.

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